Irrigated Mountain Meadow Fertilizer Application Timing Effects on Overland Flow Water Quality

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ABSTRACT

Nonpoint-source pollution from agricultural activities is currently the leading cause of degradation of waterways in the United States. Applying best management practices to flood-irrigated mountain meadows may improve agricultural runoff and return flow water quality. Prior research has focused on fertilizer use for increased hay yields, while few studies have investigated the environmental implications of this practice. We examined the effects of fertilizer application timing on overland flow water quality from an irrigated mountain meadow near Gunnison, Colorado. Application of 40 kg phosphorus (P) and 19 kg nitrogen (N) ha^{-1} using monoammonium phosphate (11–52–0, N–P–K) fertilizer to plots in the fall significantly reduced concentrations of reactive P and ammonium N in irrigation overland flow compared with early or late spring fertilization. Reactive P loading was 9 to almost 16 times greater when fertilizer was applied in the early or late spring, respectively, compared with in the fall. Ammonium N followed a similar trend with early spring loading more than 18 times greater and late spring loading more than 34 times greater than loads from fall-fertilized plots. Losses of 45% of the applied P and more than 17% of the N were measured in runoff when fertilizer was applied in the late spring. These results, coupled with those from previous studies, suggest that mountain meadow hay producers should apply fertilizer in the fall, especially P-based fertilizers, to improve hay yields, avoid economic losses from loss of applied fertilizers, and reduce the potential for impacts to water quality.

Mountain meadows generally produce low forage yields and tend to have low soil fertility, but are capable of high productivity with fertilization and proper irrigation (Siemer, 1984). Nitrogen (N) and phosphorus (P) are the primary nutrients that limit productivity in these irrigated meadows (Mortvedt et al., 1996). Therefore, N and P fertilizers and manures are traditionally applied in the spring to increase hay yields (Rumburg and Siemer, 1974; Ludwick, 1979). Although essential for maximum plant productivity, surplus N and P can lead to nutrient runoff and degradation of fresh waters (Sharpley et al., 1994; Trachtenberg and Ogg, 1994; Haygarth et al., 1998). While many nutrient management studies have focused on fertilizer source, method, and rate, as well as application timing, in relation to increasing plant production (Ludwick et al., 1978; Long et al., 1991), few studies have focused on fertilizer application timing related to environmental issues. Therefore, studies are needed to determine the appropriate application timing of fertilizer to minimize impacts to environmental variables such as water quality.

Flood irrigation is a common management practice used throughout the western United States and is the dominant practice in mountain meadows (United States Geological Survey, 2000). While fertilizing mountain meadows provides a potential source of pollutants (Korentager et al., 1991; Beegle et al., 2000), flooding with irrigation water provides a transport pathway in overland flow (Haygarth and Sharpley, 2000). With both a source and a pathway, dissolved and particulate N and P nutrients from meadows can move as nonpoint-source (NPS) pollution in return flows to adjacent receiving waters and potentially threaten water quality of streams and rivers (Miller et al., 1984; Brenner and Mondok, 1995).

Best management practices (BMPs) allow agricultural producers to balance economic and environmental needs in their operations. Using appropriate BMPs can lessen the cumulative effects of agricultural NPS pollution on adjacent water systems. Previously developed for many agricultural crops, fertilizer application BMPs need to be developed for mountain meadows. Fertilizer is typically applied to these meadows in April as producers prepare fields for the irrigation season that runs from early May to late July, but other options need to be investigated. The objective of this study was to determine how application timing of monoammonium phosphate (MAP, 11–52–0) fertilizer affected irrigation overland flow water quality. These data, integrated with past research results, may then be used to develop plausible and sustainable BMPs for mountain meadow fertilization to reduce nutrient losses in irrigation runoff.

MATERIALS AND METHODS

Study Area

The study site was located 10 km east of Gunnison, Colorado along the lower reach of Tomichi Creek at an elevation of 2375 m. Characteristics of this site include a shallow water table and deep, poorly drained, gravelly loam, floodplain soils of the Irim loam association (loamy skeletal, mixed, superactive, frigid Typic Endoaquoll) that have a 5- to 10-cm surface organic horizon of partially decomposed plant material (Hunter and Spears, 1975). The meadow vegetation found throughout this site included a mix of native and introduced perennial, cool-season species dominated by meadow foxtail (*Alopecurus pratensis* L.), various sedges (*Carex* spp.), and baltic rush (*Juncus balticus* Willd.). Livestock, excluded from the study plots

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Abbreviations: MAP, monoammonium phosphate fertilizer; NPS, nonpoint source.

from October 2000 to July 2001, have historically been grazed in a rotation plan at a moderate intensity during the fall, winter, and early spring. To increase hay yields, diammonium phosphate (18–46–0) fertilizer has been applied when needed based on soil tests at a rate of 40 kg P and 35 kg N ha^{-1} in the spring, most recently in April of 2000, before the initiation of flood irrigation. More than 99% of irrigated land in the Tomichi watershed is flood irrigated (United States Geological Survey, 1990).

Sampling Program and Chemical Analyses

A plot experiment was designed to determine how fertilizer application timing affected water quality of irrigation overland flow. A randomized complete block design with four treatments and three replicates was located immediately below an irrigation ditch. Twelve 3- × 9-m plots were aligned next to each other on approximately a 3% slope away from the ditch and were delineated with metal borders. The slope of most irrigated mountain meadows ranges from 1 to 5% (Hunter and Spears, 1975). Three fertilizer application timing treatments were implemented in which MAP was broadcast-applied by hand at a rate of 40 kg P and 19 kg N ha^{-1}. Fall application was on 26 Oct. 2000, early spring on 20 Mar. 2001, and late spring just before simulated flood irrigation on 23 Apr. 2001. A fourth treatment consisted of an unfertilized control.

Simulated flood irrigation was applied to each plot on 24 and 25 Apr. 2001, just before the start of actual irrigation. Water was pumped from the nearby irrigation ditch and applied at an equivalent rate of 171 mm h^{-1} as sheet flow onto each plot for one hour of runoff (Wolfe et al., 2000). This rate was based on flow depths of approximately 1.2 cm observed on surrounding irrigated meadows. Grab samples of overland flow were collected as runoff from the lower end of each plot using a slight modification of the SERA-IEG 17 (2002) rainfall-runoff protocol. Starting 2.5 min after runoff commencement, samples were taken every 5 min for 30 min and every 10 min thereafter until 62.5 min after runoff initiation. Source water samples were collected from the ditch water at the initiation of each plot irrigation and 30 min after runoff ensued. Temperature-calibrated pH measurements and temperature of all water samples were taken with an Orion[1] meter (Thermo Orion, Beverly, MA) at the time of grab sample collection. A precalibrated, critical-depth flume equipped with an ISCO1 3230 bubbler flow meter (Isco, Lincoln, NE) was used to measure runoff from each plot. Water samples were analyzed within 4 h for reactive P, as PO_4–P, with the ascorbic acid method and ammonium N, as NH_4–N, with the phenate method (Standard Methods 4500-P and 4500-NH_3, respectively; Clesceri et al., 1998).

Topsoil samples (7.5 cm deep without surface detritus, 10 $plot^{-1}$) were randomly collected from each plot with a 1.9-cm-diameter tube sampler and composited: (i) before fertilizer application (26 Oct. 2000), (ii) after all treatments had been applied and just before the irrigation event (23 Apr. 2001), and (iii) after hay harvest (24 July 2001). These samples were analyzed to determine basic soil characteristics and soil test levels. Nitrate and ammonium nitrogen were extracted with 2 *M* potassium chloride (KCl) and phosphorus with 0.5 *M* sodium bicarbonate ($NaHCO_3$). All extracts were colorimetrically analyzed, reactive P with the Olsen P ascorbic acid method (Olsen et al., 1954), ammonium N with a salicylate and hypochlorite reaction (Sparks, 1996), and nitrate N with a low buffer solution and a diazotizing and coupling color development reagent reaction (Self and Rodriguez, 1998).

Hay yield was determined by harvesting the center of each plot in a 1- × 10-m swath at a 7.5-cm height on 24 July 2001 using a walk-behind, sickle-bar mower. Vegetation from the mowed area was gathered and weighed wet in the field. A subsample of approximately 725 g was collected for each plot, weighed in the field, oven-dried at 60°C for 72 h, and reweighed to determine dry matter content. Dry matter yield of each plot was calculated by multiplying the percent dry matter from the subsample by the wet plot weight.

Data Manipulation

Mass balance estimations were computed to determine the relative amount of nutrient applied as fertilizer and in the irrigation water that moved off each plot in the overland flow runoff. First, nutrient fluxes were calculated by multiplying the concentration of a given nutrient from the grab samples by the flow at the point in time the sample was taken. Next, each flux was averaged with the previous flux, converted to loading rates by time period, and then multiplied by the time period between the two to determine the load by sample period. All loads were then summed to obtain the total load of nutrient moved off each plot over the irrigation event. To determine the source water load of nutrient placed on each plot, nutrient concentrations from the two source water samples were averaged and multiplied by the total amount of water applied over the irrigation event. Finally, this allowed creation of a mass balance that determined the portion of nutrient applied that was lost in runoff from each plot.

Statistical Analyses

Exploratory tests in SAS Version 8.2 (SAS Institute, 2002) produced normal distributions for log-transformed nutrient data, and therefore, logs of the raw data were used in all statistical analyses. Water quality of overland flow runoff over time was analyzed using repeated measures analysis of covariance with runoff volume as the covariate and nutrient concentrations as the dependent variables. Reactive P and ammonium N concentrations and loads were compared using PROC MIXED in SAS to determine statistical differences among all fertilizer application timing treatments. The Bonferroni method was employed in nutrient comparison analyses to control Type I errors, with $\alpha' = 0.0008$ ($\alpha' = \alpha$/number comparisons = 0.05/60) (SAS Institute, 2002). Soil nutrients were analyzed using PROC GLM in SAS to determine statistical differences among application times within sample collection dates. Treatment means of soils data were compared using Tukey's method to control the maximum experimentwise error rate at $\alpha = 0.05$ (Ott, 1993). Pairwise comparisons were made on total nutrient loads and hay yields using LSMEANS within the GLM procedure of SAS to determine significant differences among treatment means.

RESULTS

The source water was alkaline with an average pH of 8.4 (±0.1). By the time the water reached the bottom of the plot, the pH of the overland flow had dropped an average of half a pH unit to 7.9 (±0.2). The temperature of the source water increased throughout the day ranging from 6.3°C in the morning to 17.0°C by late afternoon (12.4 ± 3.5°C). Spreading the water over the plot led to an average increase in water temperature of 1.3°C (13.7 ± 3.6°C).

[1] Mention of a trademark proprietary product does not constitute endorsement by the Colorado Agricultural Experiment Station.

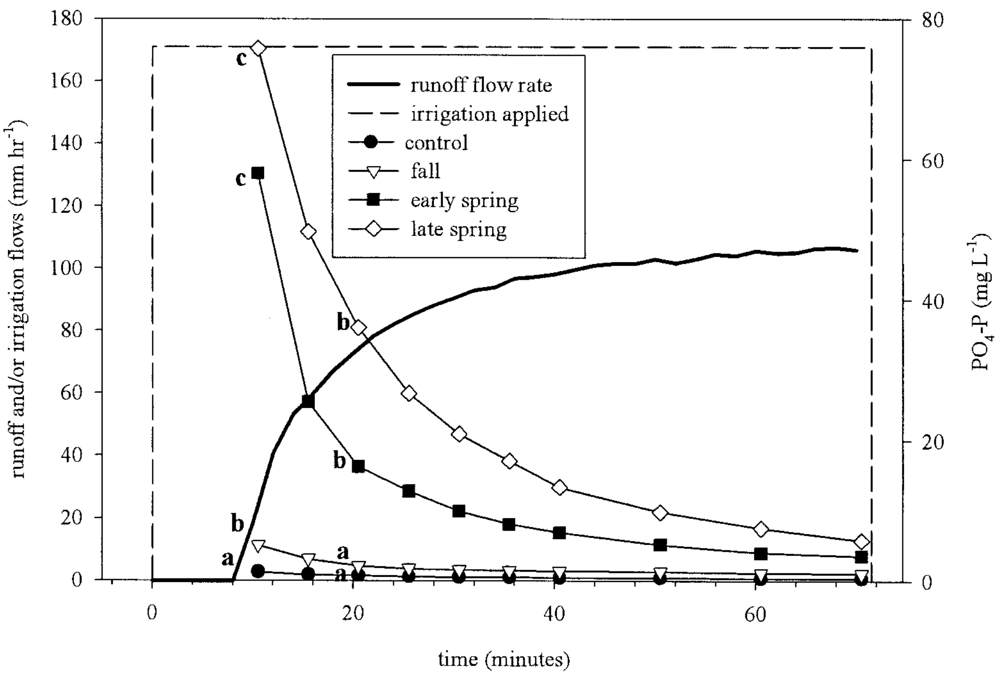

Fig. 1. Runoff hydrograph and reactive phosphorus concentrations in overland flow over the irrigation event as affected by time of application of monoammonium phosphate (11–52–0) fertilizer to a mountain meadow near Gunnison, Colorado. At a given time, means followed by the same letter are not significantly different according to Bonferonni's adjusted probability level of 0.0008 (0.05/60). Mean separations were based on log-transformed data with changes in statistical difference noted by a change in letters.

Comparison of nutrient concentrations in the irrigation overland flow from each fertilizer treatment over time showed that all treatments exhibited a pattern of decline with the highest nutrient concentration in the initial flush of water (Fig. 1 and 2). Using the Bonferonni adjusted α' of 0.0008, statistical comparisons of nutrient concentrations demonstrated that, in general, both nutrients in overland flow runoff over time, reactive P (P = 0.0016 to 0.0011) after 12.5 min and ammonium N (P = 0.1133 to 0.2018) for the entire event, from fall-fertilized plots were not significantly different from control plot runoff, while early spring (P = <0.0001 to 0.0002) and late spring (P = <0.0001) treatments were always higher than the control (Fig. 1 and 2). Nutrient concentrations became nonsignificant ($P \geq 0.0008$) between fall and early spring treatments at 52.5 min after runoff initiation for ammonium N and nearly nonsignificant (P = 0.0004) at 62.5 min for reactive P. In addition, nutrient concentrations in overland flow from early and late spring treatments were never significantly different ($P \geq 0.0008$) from each other. Median nutrient concentrations over the irrigation event were significantly different among all treatments for both reactive P and ammonium N (Table 1).

For both nutrients, loading rates (Table 2) tended to decline slightly over time with the control and fall treatments never significantly different from each other and the early and late spring treatments never significantly different from each other. For ammonium N, differences between fall and early spring became nonsignificant at 17.5 min post-runoff and differences between the control and early spring treatments were no longer significant at 62.5 min. When examining reactive P, the difference between fall and early spring became nonsignificant at 52.5 min after runoff initiation.

Loading budgetary analyses illustrated that 2.8, 25.6, and 44.7% of the reactive P placed on plots was moved off of the fall, early spring, and late spring treatments, respectively (Table 3). This was an increase in reactive P loading of 9 times from the early spring treatment and almost 16 times from the late spring treatment compared with the fall treatment. This site was a source of P, in that more reactive P was lost from the control plots than was added in the irrigation water. Analyses revealed 0.5, 9.1, and 17.2% of the applied ammonium N moved off of the fall, early spring, and late spring treatments, respectively, creating early spring loading more than 18 times greater and late spring loading more than 34 times greater than loads from the fall-fertilized plots (Table 4). This site was also a minor source for N, because more ammonium N was lost from the control plots than was added in the irrigation water. Comparisons of total loads from each plot produced significant differences among all treatment means for reactive P ($P < 0.0001$ to 0.0011, Table 3). The same comparisons of ammonium N loads revealed no difference (P = 0.0761) between the control and fall fertilization treatment, while both early and late spring treatments were higher ($P < 0.0001$, Table 4).

Topsoil samples demonstrated high background soil test levels of both extractable P and ammonium N on this site, averaging 29 and 58 mg kg^{-1}, respectively, and comparatively low nitrate N at 1.4 mg kg^{-1} (Table 5). All fertilizer treatments increased soil test levels in the April sample, but by the July hay harvest, P and nitrate N were again similar to background levels, while ammonium N dropped to 16 mg kg^{-1}. Notably, P on the control

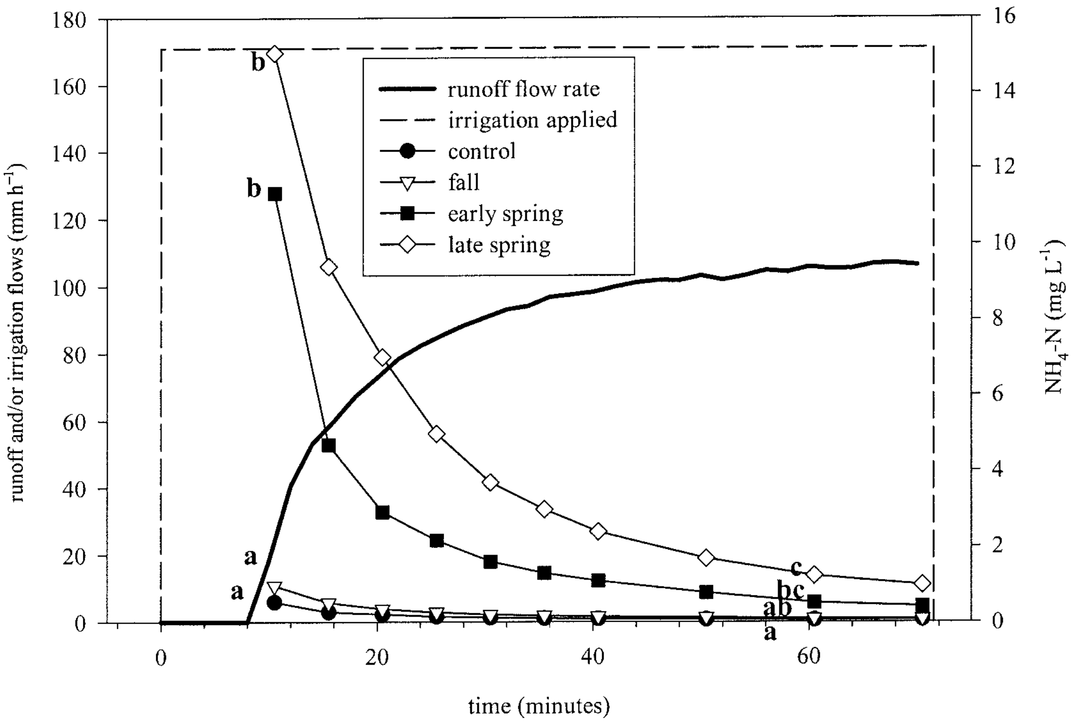

Fig. 2. Runoff hydrograph and ammonium N concentrations in overland flow over the irrigation event as affected by time of application of monoammonium phosphate (11–52–0) fertilizer to a mountain meadow near Gunnison, Colorado. At a given time, means followed by the same letter are not significantly different according to Bonferonni's adjusted probability level of 0.0008 (0.05/60). Mean separations were based on log-transformed data with changes in statistical difference noted by a change in letters.

plots showed a decreasing trend between October 2000 and July 2001 and the late spring treatment demonstrated a considerable loss of soil P following irrigation, possibly due to lack of time for incorporation into the soil. However, these differences were not statistically significant.

Averaged by treatment, hay yields ranged from 7480 kg ha^{-1} in the fall treatment to 8210 kg ha^{-1} in the early spring treatment with no significant differences (P = 0.4061 to 0.8523) among yields for any treatment.

DISCUSSION

Mountain meadows are found throughout the western United States at elevations above 1524 m (Willhite and Rouse, 1961). These meadows have been improved over time by installing irrigation systems (primarily flood), adding fertilizer, and seeding improved plant species to provide forage for livestock production. Adding fertilizer to mountain meadows, however, provides a potential source of nutrients that can be easily transported in the overland flow of flood irrigation water as NPS pollution. Return flow from agricultural fields is generally higher in nutrients than the input irrigation water (Miller et al., 1984). Although overland flow is not subject to regulatory water quality standards and nutrient concentrations will be diluted when entering a waterway as return flow, the effects of NPS pollution are cumulative, and higher nutrient levels entering a water system are of concern because of the potential for eutrophication (Smith et al., 1993, 2001a, b; Sharpley et al., 2000; Withers et al., 2000).

Results from our study indicated that timing of application of MAP fertilizer to a mountain meadow significantly affected the amount of both reactive P and ammonium N that was transported in overland flow. Regardless of application timing, all treatments exhibited an initial flush of nutrients (Fig. 1 and 2). Of the three application times investigated, applying MAP in the fall provided the best alternative for reducing the amount of both nutrients in overland flow compared with the control. The study area receives the majority of its precipitation as snowfall from October to April (Colorado Climate Center, 2002). This snow generally melts slowly in the spring months, generating little potential for runoff compared with the spring irrigation event. For P, fall application allowed a greater length of time for fertilizer pellet dissolution and movement through the thatch into the upper few centimeters of soil (Ludwick and Rumburg, 1976; Lauer, 1988) where it probably adsorbed to soil colloids or precipitated and

Table 1. Median concentrations of reactive phosphorus and ammonium nitrogen in overland flow runoff as affected by time of application of monoammonium phosphate (11–52–0) fertilizer to a mountain meadow near Gunnison, Colorado.

Treatment	Reactive phosphorus	Ammonium nitrogen
	mg L^{-1}	
Control	0.53a†	0.11a
Fall	1.02b	0.16b
Early spring	8.15c	1.47c
Late spring	18.12d	3.46d

† Within columns, medians followed by the same letter are not significantly different (α = 0.05). Median separations were based on log-transformed data.

Table 2. Loading rates of reactive phosphorus and ammonium nitrogen over the irrigation event as affected by time of application of monoammonium phosphate (11–52–0) fertilizer to a mountain meadow near Gunnison, Colorado.

Collection time	Reactive phosphorus loading rates				Ammonium nitrogen loading rates			
	Control	Fall	Early spring	Late spring	Control	Fall	Early spring	Late spring
min	$g\ ha^{-1}\ min^{-1}$							
2.5	5.2a†	19.2a	228.9b	238.6b	2.1a	3.9a	45.4b	47.8b
7.5	10.7a	37.5a	382.3b	526.5b	3.6a	7.0a	74.3b	102.4b
12.5	11.3a	34.0a	273.2b	546.7b	3.1a	5.8a	50.4b	104.4b
17.5	11.3a	30.1a	226.9b	466.0b	2.8a	4.9ab	39.8bc	88.3c
22.5	10.6a	28.2a	196.3b	379.7b	2.3a	3.9ab	32.8bc	68.8c
27.5	10.1a	27.5a	163.5b	318.9b	2.0a	3.3ab	26.7bc	55.5c
32.5	9.9a	27.0a	139.9b	264.1b	1.8a	2.9ab	22.6bc	46.2c
42.5	9.6a	26.1a	116.8b	205.0b	1.5a	2.5ab	18.1bc	35.9c
52.5	8.9a	24.1ab	90.9bc	158.2c	1.3a	2.1ab	12.9bc	26.7c
62.5	8.0a	22.1ab	75.7bc	126.7c	1.3a	1.8a	9.4ab	21.1b

† Within rows for a given nutrient, means followed by the same letter are not significantly different according to Bonferonni's adjusted probability level of 0.0008 (0.05/60). Mean separations were based on log-transformed data.

consequently became unavailable for runoff (Morgan, 1997; Bush and Austin, 2001). Likewise, the fall application allowed ammonium to move into the soil profile and attach to exchange sites or be taken up by plants in small amounts. Plant uptake would have been minimal at this time of year because plants were just beginning to break dormancy. In contrast to P, ammonium could also be lost through other pathways including volatilization and nitrification, although these would be minor under the cool soil conditions from October to late April in mountain meadows.

A budgetary approach to quantify possible environmental implications of different application times was used to determine what portions of nutrients placed on a site were transported off (Haygarth et al., 1998). Both reactive P and ammonium N loss increased from fall to early spring to late spring (Tables 3 and 4). This not only demonstrated that fall fertilization potentially reduces environmental degradation of water quality compared with spring fertilization, but loss of nearly half of the applied P (45%) and over 17% of the ammonium N from the late spring application in the first hour of irrigation has substantial economic implications.

Irrigation water interacts with soil, and therefore, soil should be considered a possible source of nutrients (McDowell and Sharpley, 2002). A linear relationship has been demonstrated between P levels in surface soil and in runoff (Pote et al., 1999), and therefore, excessive soil nutrients increase the probability of nutrient movement in overland flow possibly affecting adjacent water systems (Smith et al., 1995; Sinaj et al., 2002). Topsoil samples were collected and results indicated an accumulation of nutrients in the soil (Table 5). The high background P soil test levels from the October samples were related to fertilizer additions the previous spring (April 2000) while the high ammonium test levels were related to manure deposition by cattle grazing the site up until the plots were established in October 2000. All treatment plot soil test levels were highest in April due to lack of plant nutrient uptake and few sorption–precipitation reactions. The decrease in soil ammonium N levels in the July sample is mainly attributable to plant uptake

Table 3. Reactive phosphorus (PO_4–P) loading budget that includes inputs from fertilizer and irrigation, output in the overland flow runoff, and percent of added phosphorus that moved off in the hour long overland flow event as affected by time of application of monoammonium phosphate (11–52–0) fertilizer to a mountain meadow near Gunnison, Colorado.

Treatment	Reactive phosphorus					
	Added as fertilizer	Irrigation water load	Total load added	Total load in runoff	Load lost—Control	In runoff
	$kg\ ha^{-1}$					%
Control	0.0	0.21	0.2	0.6a†	0.0	–
Fall	40.0	0.20	40.2	1.7b	1.1	2.8
Early spring	40.0	0.20	40.2	10.9c	10.3	25.6
Late spring	40.0	0.21	40.2	18.6d	18.0	44.7

† Within a column, means followed by the same letter are not significantly different ($\alpha = 0.05$). Mean separations were based on log-transformed data.

Table 4. Ammonium nitrogen (NH_4–N) loading budget that includes inputs from fertilizer and irrigation, output in the overland flow runoff, and percent of added ammonium nitrogen that moved off in the hour-long overland flow event as affected by time of application of monoammonium phosphate (11–52–0) fertilizer to a mountain meadow near Gunnison, Colorado.

Treatment	Ammonium nitrogen					
	Added as fertilizer	Irrigation water load	Total load added	Total load in runoff	Load lost—Control	In runoff
	$kg\ ha^{-1}$					%
Control	0.0	0.03	0.0	0.1a†	0.0	–
Fall	19.0	0.02	19.0	0.2a	0.1	0.5
Early spring	19.0	0.01	19.0	1.9b	1.7	9.1
Late spring	19.0	0.02	19.0	3.4c	3.3	17.2

† Within a column, means followed by the same letter are not significantly different ($\alpha = 0.05$). Mean separations were based on log-transformed data.

Table 5. Soil test levels (0–7.5 cm) collected over the period of study as affected by time of application of monoammonium phosphate (11–52–0) fertilizer to a mountain meadow near Gunnison, Colorado. Samples were collected on 26 Oct. 2000, 23 Apr. 2001, and 24 July 2001.

Treatment	Reactive phosphorus			Ammonium nitrogen			Nitrate nitrogen		
	October	April	July	October	April	July	October	April	July
	mg PO_4–P kg^{-1}			mg NH_4–N kg^{-1}			mg NO_3–N kg^{-1}		
Control	29.4a†	32.4a	24.5a	67.7a	68.7a	15.6b	1.7a	4.2a	1.8a
Fall	29.4a	49.2a	33.5a	66.2a	64.2ab	16.0a	1.2a	3.7a	1.6a
Early spring	28.6a	71.3a	35.5a	48.5a	88.4b	16.5a	1.4a	5.5a	1.5a
Late spring	30.4a	56.9a	28.6a	50.1a	99.8ab	15.7ab	1.3a	5.4a	1.7a

† Within columns, means followed by the same letter are not significantly different ($\alpha = 0.05$). Mean separations were based on log-transformed data.

as well as various losses from volatilization, immobilization, and leaching following nitrification to nitrate. Much of the late spring–applied P, not yet adsorbed to soils, was removed by flood irrigation while P placed the previous fall or even early in the spring was comparatively retained in the soil. Despite high soil test P levels, runoff values were low in controls, demonstrating that the threat to water quality is primarily from applied fertilizer sources.

A previous study in the Gunnison Basin demonstrated that fall-applied P fertilizer results in greater yields relative to spring applications (Ludwick and Rumburg, 1976). However, no significant hay yield increases were observed in the present study because recent applications (April 2000) of P to the site and the ability of P to carry into future growing seasons (Siemer, 1984) made the site nonresponsive to further nutrient application. Supported by both water quality and soil nutrient results, this study established that water quality of irrigation overland flow runoff tends to be most affected by fertilizer applied in the late spring just before initiation of irrigation and least affected by fertilizer applied in the fall. It confirmed that fall-applied fertilizer tends to be less available for transport in spring runoff or flood irrigation, hence lessening possible water quality impacts. This strengthens findings by Bush and Austin (2001), who stated that delaying irrigation after fertilization reduces the amount of reactive P available for movement.

CONCLUSIONS

Relationships between water quality and irrigated agricultural practices were assessed from this fertilizer application timing study. The diffuse nature of NPS pollution makes its control the focus of many best management practices today and practices need to be developed that provide both economically and environmentally sustainable yields for mountain meadow hay producers. This study determined that application of MAP fertilizer in the fall significantly reduced the concentration of both reactive P and ammonium N in flood irrigation overland flow compared with applying fertilizer in the early or late spring. In contrast to the traditional practice of spring application of P-based fertilizers, fall application has been shown in a previous study to provide improved hay yields, and this study clearly demonstrated reduced water quality impacts. In many respects, fall fertilizer application should be more feasible than spring application, with dryer meadows and lighter work loads for both producers and fertilizer applicators. With environmental, agronomic, and economic implications, it can be concluded that fall application of P-based fertilizer is superior to spring application in P-deficient flood-irrigated mountain meadows.

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